DISCOVERY OF THE TWO-PROTON DECAY OF ^{45}Fe*

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In experiments performed at the GSI Fragment Separator and at the GANIL SISSI-LISE3 facility the decay of ^{45}Fe has been investigated. Implantation events of ^{45}Fe ions, stopped in silicon telescopes, were correlated with radioactive decay events. The decay energy spectra exhibit a peak of an average energy of (1.14 ± 0.05) MeV. This observation, together with the non-observation of coincident γ or β events, represent clear evidence for the two-proton ground state decay of ^{45}Fe. The average half-life of ^{45}Fe, deduced from both experiments, is $T_{1/2} = 3.8^{+2.0}_{-0.8}$ ms.

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1. Introduction

The emission of two protons from an excited nuclear state is known experimentally since 1983 when such a decay mode was observed for states populated in the β-decay of ^{22}Al and ^{26}P [1, 2]. Since then, several other beta-delayed two-proton emitters has been investigated, see for example Ref. [3]. The decay mechanism of all these cases was found to be consistent with sequential one-proton emission through the intermediate nucleus. Two proton emission was also established for excited states populated via resonance reactions. One such case is the 2^+ resonance in ^{14}O at 7.77 MeV which was found to decay sequentially via states in ^{13}N [4]. Another interesting example, measured recently, is the 1^- 6.15 MeV state in ^{18}Ne [5]. Although in this case no excited states in ^{17}F through which the sequential emission could proceed are known, the possibility of transitions via tails of higher lying broad resonances is not yet excluded.

The emission of two protons from the ground state was observed in two cases: ^{6}Be [6] and ^{12}O [7]. In both of them, however, the initial state as well as the ground state of the intermediate nucleus are broad and the decay can proceed sequentially through the tail of the latter. These are examples of the so called "democratic" decay which occurs when the energy of the first proton is comparable with the width of the intermediate state.

The case of "pure" two-proton radioactivity, as defined by Goldansky already in 1960 [8], may occur when the emission of one proton is energetically not allowed which requires that the energy difference between the ground states of the initial and the $1p$ daughter nuclei is larger than the sum of their widths. Such a process, predicted for medium-mass, even-Z, proton-rich nuclei, where due to the Coulomb barrier the relevant states are narrow, was never observed to date despite considerable experimental efforts. Shell model calculations [9, 10] and Coulomb-energy systematics [11] have identified a few candidates for this decay mode. One of them, ^{45}Fe, was predicted to decay either by $2p$ emission with a Q-value of about 1 MeV or by EC decay with a $Q_{\mathrm{EC}} \approx 19$ MeV.

^{45}Fe was observed for the first time by Blank *et al.* [12] at GSI Darmstadt by the in-flight identification of fragmentation products of a 600 MeV/nucleon ^{58}Ni beam. Since then, attempts to study the decay mode of ^{45}Fe were undertaken both at SIS-FRS facility of GSI Darmstadt and SISSI-LISE3 system of GANIL Caen [13, 14]. Here we report briefly on the latest experiments, performed at both laboratories, which succeeded in the observation of the ^{45}Fe decay and which yielded the first evidence for $2p$ radioactivity of this nucleus. Detailed descriptions of the experiments have been published in Refs [15, 16].

2. Experiment at GSI

In the GSI experiment proton-rich nuclei were produced by projectile fragmentation of a 650 MeV/nucleon ^{58}Ni beam impinging on a 4 g/cm^2 beryllium target. The average beam intensity was about 4×10^9 ions per spill of 2 s length and a repetition period of 7.6 s. Selected reaction products were transmitted through the Fragment Separator (FRS) and identified in-flight by the standard ΔE-$B\rho$-TOF method. Energy loss (ΔE) information was provided by the four-fold ionization chamber MUSIC. Three plastic scintillators, mounted at the second, third and final focal planes of the FRS, were used to measure horizontal position necessary for the magnetic rigidity ($B\rho$) determination as well as for the time-of-flight (TOF) measurement. As a result, the atomic number Z and the mass-to-charge ratio A/q could be determined for each ion transmitted to the final focal plane.

After passing the identification detectors, the ions were slowed down in an aluminium degrader of variable thickness and implanted into a stack of 8 Si detectors, each 300 μm thick and 60 mm in diameter. Since the range straggling of the slowed-down iron isotopes in silicon was about 600 μm (FWHM), the total thickness of the Si telescope (2.4 mm) was sufficient to stop all of them. The telescope was mounted inside a NaI(Tl) barrel composed of six 30 cm long crystals. Its purpose was to discriminate β^+ decay events which are accompanied by two 511 keV annihilation quanta. The implantation setup is shown schematically in the left part of figure 1. The whole detection system was calibrated by implanting the known β-delayed (βp) proton emitters ^{49}Fe and ^{50}Co. In particular it was found that the total efficiency for detecting a γ ray in the NaI barrel for a βp energy range of 0.9–4 MeV was 93 %. The average energy resolution (FWHM) of the Si detectors was found to be about 250 keV for a 2 MeV proton energy.

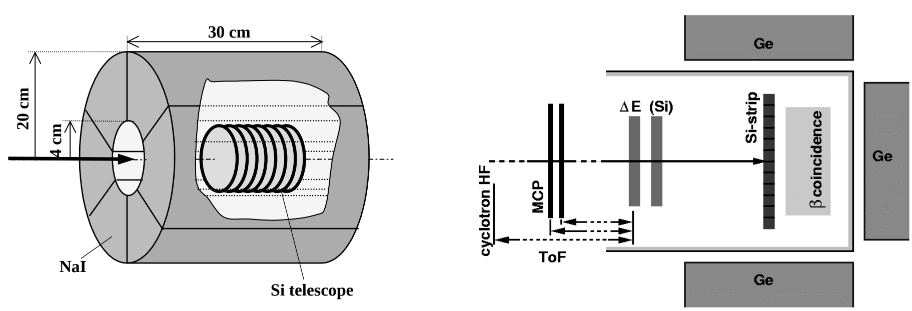

Fig. 1. Schematic drawings of the implantation setups used in the GSI experiment (left) and in the GANIL experiment (right).

Two principal difficulties of charged particle spectroscopy at the FRS are: *(i)* large energy (up to about 1 GeV) released in a Si detector by a stopping ion, and *(ii)* relatively high intensity of contaminant ions (about 200 ions/s) entering the Si telescope during each beam spill. To overcome these difficulties a set of newly developed preamplifiers with a fast reset function was used. The fast reset preamplifiers could be switched-off by an external logical signal for about 2 μs after the arrival of a heavy ion. Such signal was generated each time an ion was passing through the first Si detector in the telescope. As a result, already 2 μs after implantation the system was sensitive to low energy radioactive decay signals. Moreover, in parallel to a standard acquisition system utilizing CAMAC ADC and TDC modules, a second data acquisition system based on the DGF-4C digital modules [17] was used. All signals from the identification detectors and from the implantation setup were processed by the DGF modules. The function of these modules consisted of digitizing each input signal with 40 MHz frequency, amplitude determination and time stamping by the on-board digital signal processor and subsequent storage in the output buffer. This acquisition system was triggered only when an ion with a low A/q ratio entered the telescope. After the trigger, all incoming signals were accepted and processed for 10 ms. Subsequently, the DGF output buffers were read out and the data stored on magnetic tape. In this way, information of all heavy ions, decays and γ-rays occurring within 10 ms after the triggering ion was collected practically *dead-time free.* A more detailed discussion of this detection technique is given in Ref. [18].

The measurement lasted about 6 days. In this time the DGF acquisition was triggered about 2000 times which corresponds to an average time of about 4 min. between registered events. The identification plot of those ions which triggered the acquisition is shown in figure 2 (left). Among them six events of ^{45}Fe are clearly seen. The 10 ms history periods recorded after each of them were carefully examined. One ^{45}Fe ion happened to be stopped in a Si detector suffering a temporary malfunction, so that no decay information was recorded. The decays of the five other ^{45}Fe ions, however, could be observed. For one of them the energy release of $\approx$ 10 MeV was found accompanied by a γ-ray of about 900 keV. Such an event is consistent with the β^+ decay of ^{45}Fe followed by a delayed proton emission. In the four other cases the implantation was followed by an energy release of about 1 MeV in the same detector. Such a pattern is expected if ^{45}Fe decays by emission of two protons. Importantly, in each of these cases no other signals were found in coincidence and no contaminant ion was stopped in the same detector between ^{45}Fe implantation and the decay event.

The possibility that the observed decay events originate from background can be tested by plotting the singles spectrum of all decay-like events collected by the Si telescope during the whole ^{45}Fe measurement. Such a spectrum collected under the additional requirement that no γ-ray was detected in coincidence is shown in figure 2 (right). Above 700 keV there are 5 counts: four of them represent events observed in correlation with ^{45}Fe ions while the remaining one could not be correlated to any ion. We assign the latter count to the random background originating from long lived activities accumulated in the telescope during the run. It follows that the probability to detect such a random event during the 10 ms observation period is of the order of 10^{-3}. This leads us to conclude that the four events correlated with the implantation of ^{45}Fe do represent the decay of this nucleus.

Finally, the average energy of the decay of ^{45}Fe is found to be (1.1 ± 0.1) MeV while the analysis of the decay times yield a half-life estimate of $T_{1/2} = 3.4^{+3.4}_{-1.1}$ ms.

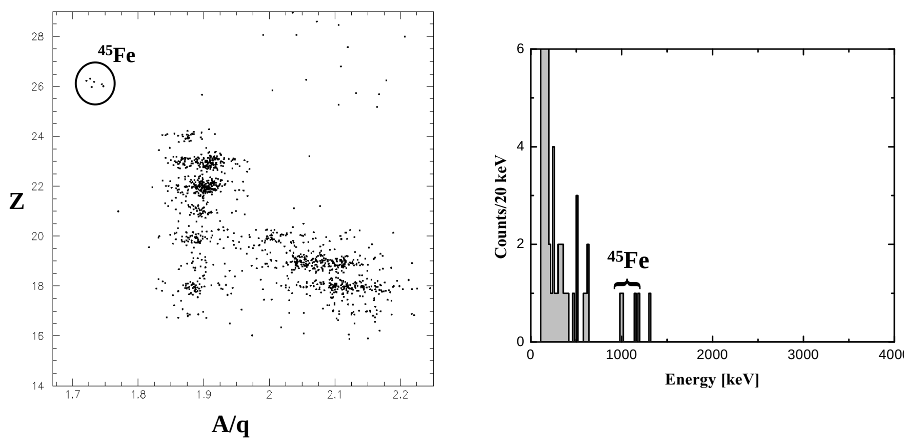

Fig. 2. Left: identification plot of ions which entered the Si telescope and triggered the DGF acquisition during the ^{45}Fe measurement at GSI. Right: singles spectrum of all decay-like events anticoincident with the NaI detectors recorded during the whole run.

3. Experiment at GANIL

In the GANIL experiment ions of interest were produced by fragmentation of a ^{58}Ni beam at 75 MeV/nucleon impinging on a 240 μm natural nickel target mounted in the SISSI device. The beam intensity varied between 3 and 5 μA. Products were separated by means of the Alpha/LISE3 spectrometer.

The detection setup consisted of two channel-plate detectors for timing purposes located at the first LISE focal point and the implantation telescope mounted at the final focus composed of 4 silicon detectors surrounded by an array of Ge detectors in a close geometry, see the right part of figure 1.

The first two Si detectors in the telescope, of 300 μm thickness, provided timing and energy-loss information. The selected ions were stopped in the third Si detector, also of 300 μm thickness, which was a double-side silicon-strip detector with 16×16 $x - y$ strips and a pitch of 3 mm. The fourth Si detector was 6 mm thick and served as a veto detector for heavy ions as well as a counter for β particles. Implantation events were triggered by the first two detectors in the telescope while radioactive decay events were triggered by the third or fourth detector. The silicon telescope was calibrated with a triple α source and with the known βp emitters ^{40}Ti and ^{36}Ca. It was found that the probability of detecting β particle in the fourth Si detector when the β decay occurred in the implantation detector was about 30 %. The total efficiency of the Ge array was about 1.6 % at 1.3 MeV.

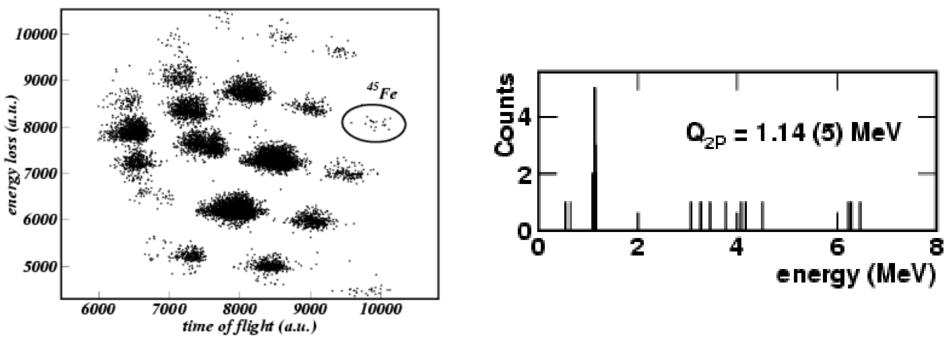

Fig. 3. Left: identification plot for ions stopped in the Si strip detector during the ^{45}Fe measurement at GANIL. Right: decay energy spectrum correlated with the ^{45}Fe implantation. Only events occurring up to 100 ms after implantation were considered.

During a 36 h measurement 22 ions of ^{45}Fe were identified (figure 3). Since the implantation rate was less then 1 ion/s in each pixel of the strip detector, correlation of decay events with the ions in the millisecond time range could be performed without difficulties. The right part of figure 3 shows the decay events correlated with ^{45}Fe ions up to 100 ms after the implantation. A distinct peak containing 12 counts at energy of (1.14 ± 0.05) MeV is clearly visible. No events in the peak were accompanied by either a β particle in the fourth detector or by a γ ray. These observations suggest that the peak originates from the direct two-proton ground-state decay of ^{45}Fe. The decay time analysis yielded a half-life value of $T_{1/2} = 4.7^{+3.4}_{-1.4}$ ms.

4. Discussion

The two experiments yield consistent results for the decay energy and the half-life of ^{45}Fe. The values obtained at GANIL are more precise due to better energy resolution and due to better statistics. An important argument in favor of $2p$ decay interpretation is the anticoincidence with γ-rays and β-particles observed in the GSI and GANIL experiments, respectively. Despite the low statistics, this argument appears to be more significant in the case of the GSI data. The chance to miss all γ-rays for the four GSI events is 2×10^{-5} while the probability to miss all β particles in 12 GANIL events is 1.4×10^{-2}. This reflects the crucial role of the setup efficiency which was equal to 93 % and 30 % for the γ (GSI) and β (GANIL) detection, respectively.

The observed decay energy of 1.14 MeV agrees well with the Q_{2p} values predicted by Brown (1.15(9) MeV) [9] and Ormand (1.28(18) MeV) [10], who applied the isobaric multiplet mass equation and the shell-model calculations of the Coulomb energy shifts, as well as with the result given by Cole (1.22(5) MeV) [11] based on the Coulomb energy systematics.

Figure 4 shows the results of various theoretical estimates of the partial half-life for the $2p$ decay of ^{45}Fe. The solid lines represent calculations within a three-body model of Grigorenko *et al.* [19] assuming either a pure p^2 or f^2 configuration for the two valence protons. The average value from the two experiments, $T_{1/2} = 3.8^{+2.0}_{-0.8}$ ms, is in good agreement with this model which yields $T_{1/2} = 3$ ms for $Q_{2p} = 1.14$ MeV and the p^2 configuration. For comparison, two predictions of the two-body R-matrix formalism assuming

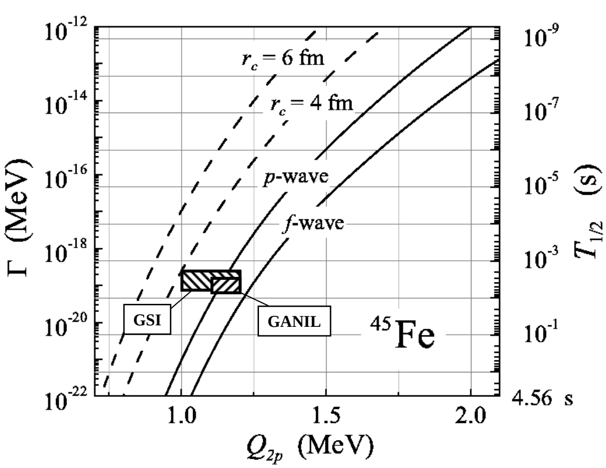

Fig. 4. Theoretical estimates of the partial half-life for the ground-state $2p$ decay of ^{45}Fe. The experimental values are indicated by the hatched boxes.

the emission of a diproton (^{2}He particle) are shown (dashed lines), corresponding to a spectroscopic factor of $\theta^2 = 1$ and channel radii r_c of 4 fm and 6 fm, respectively. The realistic value of $\theta^2 = 0.195$ [20] would increase these half-lives by a factor of 5 yielding $T_{1/2} = 0.15$ ms for $r_c = 4$ fm and $Q_{2p} = 1.14$ MeV. This suggests that the simple two-body approximation may not be adequate for the description of the $2p$ radioactivity.

5. Summary

The decay of ^{45}Fe has been studied in two experiments performed at GSI Darmstadt and at GANIL Caen. Both yielded consistent results suggesting the emission of particle(s) of total energy of 1.14 ± 0.05 MeV with a half-life of $T_{1/2} = 3.8^{+2.0}_{-0.8}$ ms. These findings, together with the nonobservation of coincident γ-rays or β particles, provide strong evidence for the two-proton ground-state radioactivity of ^{45}Fe. This is the first case of such a decay mode having been established for a narrow nuclear ground state. Further experiments are necessary to confirm the result, in particular by separate detection of the two emitted protons. Measurements of the energy and the angular correlation of the two protons are needed to determine the mechanism of the $2p$ radioactivity and to answer the question whether a diproton state contributes to the process.

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REFERENCES

[1] M.D. Cable *et al.*, *Phys. Rev. Lett.* **50**, 404 (1983).

[2] J. Honkanen *et al.*, *Phys. Lett.* **133B**, 146 (1983).

[3] H.O.U. Fynbo *et al.*, *Nucl. Phys.* **A677**, 38 (2000) and references therein.

[4] C.R. Bain *et al.*, *Phys. Lett.* **B373**, 35 (1996).

[5] J. Gómez del Campo *et al.*, *Phys. Rev. Lett.* **86**, 43 (2001).

[6] O.V. Bochkarev *et al.*, *Sov. J. Nucl. Phys.* **55**, 955 (1992).

[7] R.A. Kryger *et al.*, *Phys. Rev. Lett.* **74**, 860 (1995).

[8] V.I. Goldansky, *Nucl. Phys.* **19**, 482 (1960).

[9] B.A. Brown, *Phys. Rev.* **C43**, R1513 (1991).

[10] E. Ormand, *Phys. Rev.* **C53**, 214 (1996).

[11] B.J. Cole, *Phys. Rev.* **C54**, 1240 (1996).

[12] B. Blank *et al.*, *Phys. Rev. Lett.* **77**, 2893 (1996).

[13] M. Pfützner in Proc. of 1st Int. Symposium on Proton Emitting Nuclei, PROCON'99, 7–9 October 1999, Oak Ridge TN, USA, ed. J.C. Batchelder, AIP Conference Proceedings 518, p. 89; J. Giovinazzo *et al.*, Proc. of 1st Int. Symposium on Proton Emitting Nuclei, PROCON'99, 7–9 October 1999, Oak Ridge TN, USA, ed. J.C. Batchelder, AIP Conference Proceedings 518, p. 321.

[14] J. Giovinazzo *et al.*, *Eur. Phys. J.* **A10**, 73 (2001).

[15] M. Pfützner *et al.*, *Eur. Phys. J.* **A14**, 279 (2002).

[16] J. Giovinazzo *et al.*, *Phys. Rev. Lett.* **89**, 102501 (2002).

[17] B. Hubbard-Nelson, M. Momayezi, W.K. Warburton, *Nucl. Instrum. Methods Phys. Res.* **A422**, 411 (1999); see also `http://www.xia.com`

[18] M. Pfützner *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A493**, 39 (2002).

[19] L.V. Grigorenko *et al.*, *Phys. Rev.* **C64**, 054002 (2001); L.V. Grigorenko *et al.*, *Phys. Rev. Lett.* **85**, 22 (2000).

[20] B.A. Brown, *Phys. Rev.* **C44**, 924 (1991).